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Research Paper

Analysing interactions among Sustainable Development Goals with Integrated Assessment Models

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ABSTRACT

To achieve all Sustainable Development Goals (SDGs) by 2030, it is necessary to understand how they interact with each other. Integrated Assessment Models (IAMs) represent many human–environment interactions and can inform policymakers about the synergies and trade-offs involved in meeting multiple goals simultaneously. We analyse how IAMs, originally developed to study interactions among energy, the economy, climate, and land, can contribute to a wider analysis of the SDGs in order to inform integrated policies. We compare the key interactions identified among the SDGs in an expert survey, with their current and planned representation in models as identified in a survey among modellers. We also use text mining to reveal past practices by extracting the themes discussed in the IAM literature, linking them to the SDGs, and identifying the interactions among them, thus corroborating our previous results. This combination of methods allowed us to discuss the role of modelling in informing policy coherence and stimulate discussions on future research. The analysis shows that IAMs cover the SDGs related to climate because of their design. It also shows that most IAMs cover several other areas that are related to resource use and the Earth system as well. Some other dimensions of the 2030 Agenda are also covered, but socio-political and equality goals, and others related to human development and governance, are not well represented. Some of these are difficult to capture in models. Therefore, it is necessary to facilitate a better representation of heterogeneity (greater geographical and sectoral detail) by using different types of models (e.g. national and global) and linking different disciplines (especially social sciences) together. Planned developments include increased coverage of human development goals and contribute to policy coherence.

1. Introduction

1.1. The 2030 agenda

With the approval of the Sustainable Development Goals (SDGs) in autumn 2015, the United Nations adopted an ambitious agenda to tackle several grand challenges of the 21st century simultaneously. This includes ending hunger and eradicating poverty while also protecting the environment through actions such as limiting the pace of climate change and protecting marine and terrestrial

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biodiversity [1]. This agenda is expressed in the form of 17 SDGs that have been broken down into 169 specific targets. A key aspect of the SDGs is 'achieving sustainable development in its three dimensions – economic, social and environmental – in a balanced and integrated manner' [1]. However, the understanding of interactions among the policies targeting different SDGs presents a gap in the knowledge [2]. Several studies have developed frameworks to examine the interactions among the SDGs, each with a different classification scheme [2–6]. While Nilsson et al. [5] emphasised the need for case studies to identify interactions, the ex-ante identification of possible interactions using a global forward-looking model-based analysis is a prerequisite. Such analyses can quantify the effort required to reach the targets and can identify the interactions among the targets in terms of synergies and trade-offs [7,8]. Examples of such interactions include the competing claims for land between bioenergy production to prevent climate change and food production to reduce hunger [9,10], and the possible synergy between climate policy and reducing air pollution [11]. A recent study by the International Council for Science (ICSU) [12] called for approaches and tools to support assessments of the nature and strength of interactions to help design implementation strategies.

Thus far, no comprehensive review has explored the possible interactions among the SDGs at a global scale (in a 17 by 17 matrix), which the ICSU [12] report called for. At the same time, some studies have used one or more SDGs as a starting point to study interactions with other SDGs [13–15]. Some have looked at interactions in a specific country [2]. Pradhan et al. [16] and Pollitt et al. [17] are the closest to a comprehensive review. Pradhan et al. [16] systematically analysed the correlations between SDG indicators in a historical time series across the 227 countries for which data was available. Though they provided insights on potential interactions among the SDGs, they were not able to distinguish between the direct causal relations and the correlations because of a confounding third factor. Pollitt et al. [17] examined the links between macroeconomic perspectives and sustainable development and reviewed their representation in models, focusing mostly on macroeconomic models in the process.

1.2. Integrated Assessment Models

Integrated Assessment Models (IAMs) offer an integrated perspective on complex human–environment interactions and can thus contribute to an assessment of the strategies to achieve multiple SDGs simultaneously. Originally, they were used to study integrated energy, land, and climate change mitigation pathways, but have since been developed further with expanded sets of interactions across sectors and systems [18,19]. Here, we assess the extent to which these models can perform wider analyses of the SDGs. IAMs have already been used systematically to study interactions between climate change mitigation and other societal priorities [20–23], including air pollution, health [24,25], energy [26,27], food [28] and water security, and biodiversity. They have done so either by incorporating these processes in the models themselves, or by linking different models, modules, or tools. IAMs have used model comparison exercises to spur development in new areas. For example, in EMF21, models collaborated to add non-CO_2 gases to the analysis. Several recent and planned model innovations can also help develop a systemic understanding of the interactions among the SDGs across different dimensions of sustainability.

IAMs come in many forms. They have a diverse range of objectives, scopes, methods, spatial and temporal dimensions, sectoral and technology representations, solution method, and anticipation (simulation or foresight). The analysis here centres on models that focus on climate change mitigation and processes (in contrast to IAMs engaging in cost-benefit analysis), but within this set, the models included span the entire spectrum of the literature for the attributes mentioned. Some notable models that are not included here have covered the SDGs more extensively, namely iSDG [29], International Futures [30], and Earth 3 [31].

1.3. Overview of this study

The objective of this paper is to analyse current practices and planned model developments in order to show how IAMs, originally developed to study interactions among energy, the economy, climate, and land, can contribute to an analysis of a wider pool of SDGs and the development of integrated policies. We first aim to understand the key interactions through experts who have tacit knowledge on how SDGs are interconnected. Next, we compare this learning with current and future representations of both the SDG targets and their interactions in well-established IAMs. We complement these results by performing a computer-aided synthesis of the IAM literature related to SDGs to better understand how IAM results have been used to discuss interactions among SDGs in the past. The model survey and literature synthesis aim to capture the tacit knowledge of what is modelled, either endogenously or through coherent assumptions, and to what extent it has been used to study interactions among SDGs. Capitalising on the results from these three complementary perspectives, we discuss the opportunities for IAMs to inform policy discussions and help identify gaps, which, in turn, can contribute to setting priorities for further research and identifying areas for collaboration. When compared to Pollitt et al. [17], the new element in our work is this combination of the two surveys of both SDG experts and IAM modellers. As Pollitt et al. [17] predated the SDGs, and IAMs have developed strongly towards broader system boundaries since then, there is a need for an update with respect to an overview of the representation of SDGs.

We established **information on key interactions** by asking a group of experts on one or more SDGs (e.g. poverty) about the existing interactions (see Methods). The survey aimed at identifying interactions among the SDGs at the goal-level, which work in various directions and even change over time. Therefore, we used only the scores for the strength of the interactions and not the scores for the direction.

To assess the suitability of the models to represent the interactions among the SDGs, we approached IAM modelling teams participating in the Linking Climate and Development Policies – Leveraging International Networks and Knowledge Sharing (CD-LINKS) project [32]. The models included here are AIM-CGE [33], China TIMES [34], DNE21+ [35], GCAM [36], GEM-E3 [37], IMAGE [38], IPAC [39], PRIMES [37], REMIND-MAgPIE [40], MESSAGE-Brazil [41], MESSAGE-GLOBIOM [42], and WITCH [43]. These models represent the state of the art of integration of SDGs in their frameworks, and include leading IAMs used in climate assessments such as those prepared by the IPCC [44] and the shared socio-economic pathways (SSP) scenarios [18], ecosystem assessments such as the Millennium Ecosystem Assessment [45] and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [46], and other integrated assessments such as the Global Environment Outlook [47], Global Energy Assessment [48], and The World in 2050 [49]. The survey comprised six questions (see Methods for the full text of the questions) related to the current model representation of individual SDGs; the planned model representation of individual SDGs; important interactions among the SDGs (in a 17x17 matrix); currently modelled interactions among the SDGs; interactions planned to be modelled; and interactions that are conceivable to be modelled in the future. For brevity, the SDG expert survey on key interactions is referred to in the following sections as the *expert survey*, while the model assessment is referred to as the *model survey* (while noting that modellers are also experts).

For the computer-aided synthesis of the existing literature, we sent a request to the Integrated Assessment Modelling Consortium (IAMC [50]) mailing list and requested an overview of the key SDG-related references for each model, which we extended with key references from the CD-LINKS [32], EMF27 [51], LIMITS [52], and PATHWAYS [53] projects (see also Methods). We applied text mining methods to full text publications to analyse the interactions among the SDGs that have been studied in the literature. As IAMs are diverse, the results below should not be interpreted as a precise mapping of everything that the entire IAM community has to offer on the SDGs. Rather, it aims to present a general overview of SDG clusters that IAMs can and cannot speak to, in order to help identify areas for further model development and collaboration with other disciplines.

2. Results

We separated the SDGs into four clusters to ease the discussion of results (see also e.g. Refs. [54,55]). This clustering is only used to simplify the presentation and discussion of our findings and does not represent any hierarchy. We acknowledge that several SDGs also have elements that can fall into other clusters. The clustering followed in this study pertains to the structure of most IAM frameworks, as the aim of this paper is to show how the IAMs deal with the SDGs (see Fig. 1 and Fig. S1): efficient and sustainable resource use (SDGs 2, 6, 7, 12); Earth system (SDGs 13, 14, 15); human development goals (SDGs 1, 3, 4, 5, 8, 10); and good governance and infrastructure (SDGs 9, 11, 16, 17) (in Fig. 1: yellow for human development goals; green for resource use; blue for Earth system; and red for governance and infrastructure). More detailed results of the surveys and the literature synthesis and an overview of the model representation of individual SDGs are presented in the supplementary material.

2.1. Key interactions in and with the human development cluster

According to the *expert survey*, key interactions (dark grey and orange in Fig. 1b) exist across all SDG clusters, but lie especially within the human development cluster, between the human development and resource use clusters (specifically the effects of economic growth and reducing poverty on other goals), and in the Earth system cluster. Experts noted that the strength and direction of the interactions often depend on the policy instruments and their implementation (see Table S1).[1]

2.2. IAMs can be expanded to deal with other social goals

2.2.1. Representation of individual SDGs: 13 at least partly quantified

Fig. 1 also includes the self-assessment of IAM modelers on the ability of their models to represent individual SDGs and their interactions. First, we assessed how many of the 169 targets included in the SDGs can be quantified by indicators that either already exist or are planned to be used in the future (see Fig. 1a and Table 1). It shows that many SDGs can at least be partly quantified by IAMs, while some are clearly not well covered in these models. The latter most notably relate to (gender) inequalities (SDGs 5 and 10, although some indicators can be found in the literature), education (SDG 4, although the International Futures model [13] has made progress in this area), and peace (SDG 16), and to some extent also cities (SDG 11) and marine life (SDG 14). Well-covered SDGs are in the 'Efficient and sustainable resource use' and 'Earth system' clusters, concerning climate (SDG 13), energy (SDG 7), land use (SDGs 2 and 15), and water (SDG 6). SDGs relating to 'Human development goals' and 'Good governance and infrastructure' are generally more difficult for IAMs to quantify fully (but see 56), especially for indicators on institutions and the existence of policies and legal frameworks (see also [57]).

2.2.2. Interactions among SDGs prevailing currently in models: resource use and earth system clusters

The asterisks show whether IAMs can represent crucial interactions among different SDGs (as pairs) based on current model versions (three asterisks in Fig. 1b, with two indicating planned developments) or whether these interactions are conceivable to be represented in the models in the future (one star in Fig. 1b). These currently represented interactions are found mostly in and between the resource use and Earth system clusters because broad coverage is necessary for the representation of climate and energy, and IAMs have developed to cover processes beyond climate change. The agreement between IAM representation (three stars) and key interactions is the highest (dark orange cells) for the effect of economic growth on all SDG clusters, the effect of energy on health and climate, the effect of consumption and production on climate and life on land, the effect of climate on other resource use and Earth system SDGs, and the effect of governance SDGs on economic growth and climate. It is important to note that some SDG interactions are fully endogenous (e.g. between access to clean energy and climate action), while others are rather part of a consistent set of exogenous assumptions as a component of a scenario narrative (e.g. between education and economic growth [58]).

The interactions best represented in IAMs (i.e. receiving the highest average scores in the *model survey*) were checked in great detail with the comments provided in the *expert survey*, to assess whether the representations of interactions in the IAMs correspond with the processes described by the experts[2] on the associated SDGs. The four interactions with the highest scores for model representation are energy affecting climate, climate affecting energy, economic growth affecting climate, and climate affecting life on land. Processes highlighted by experts generally agree with model representations of these interactions, although the experts mentioned detailed dynamics that are not always covered by the models, such as how access to clean cooking reduces demand for biomass (see Table 2 for a mapping of expert-defined processes and model representations for these highest ranked interactions, and Table S1 for all comments on interactions from the *expert survey*). The experts' comments highlight the need to develop IAMs further and to use them in combination with other tools and approaches.

2.2.3. SDG interactions planned to be modelled: increasing coverage of human development

In addition to resource use and Earth system clusters that are currently modelled, model developments in the planning stages include interactions between resource use and human development goals, while interactions that are conceivable to be modelled further include governance and infrastructure goals, most notably regarding cities. Interactions planned to be covered generally show

[1] For a comparison between the *expert survey* and the empirical analysis by Pradhan et al. (*16*), see Supplementary Information (Fig. S2). See Table S1 and Fig. S3 for disaggregated results on important interactions according to both the *model* and *expert surveys*.

[2] These SDG experts were not necessarily aware of or connected to the IAMs.

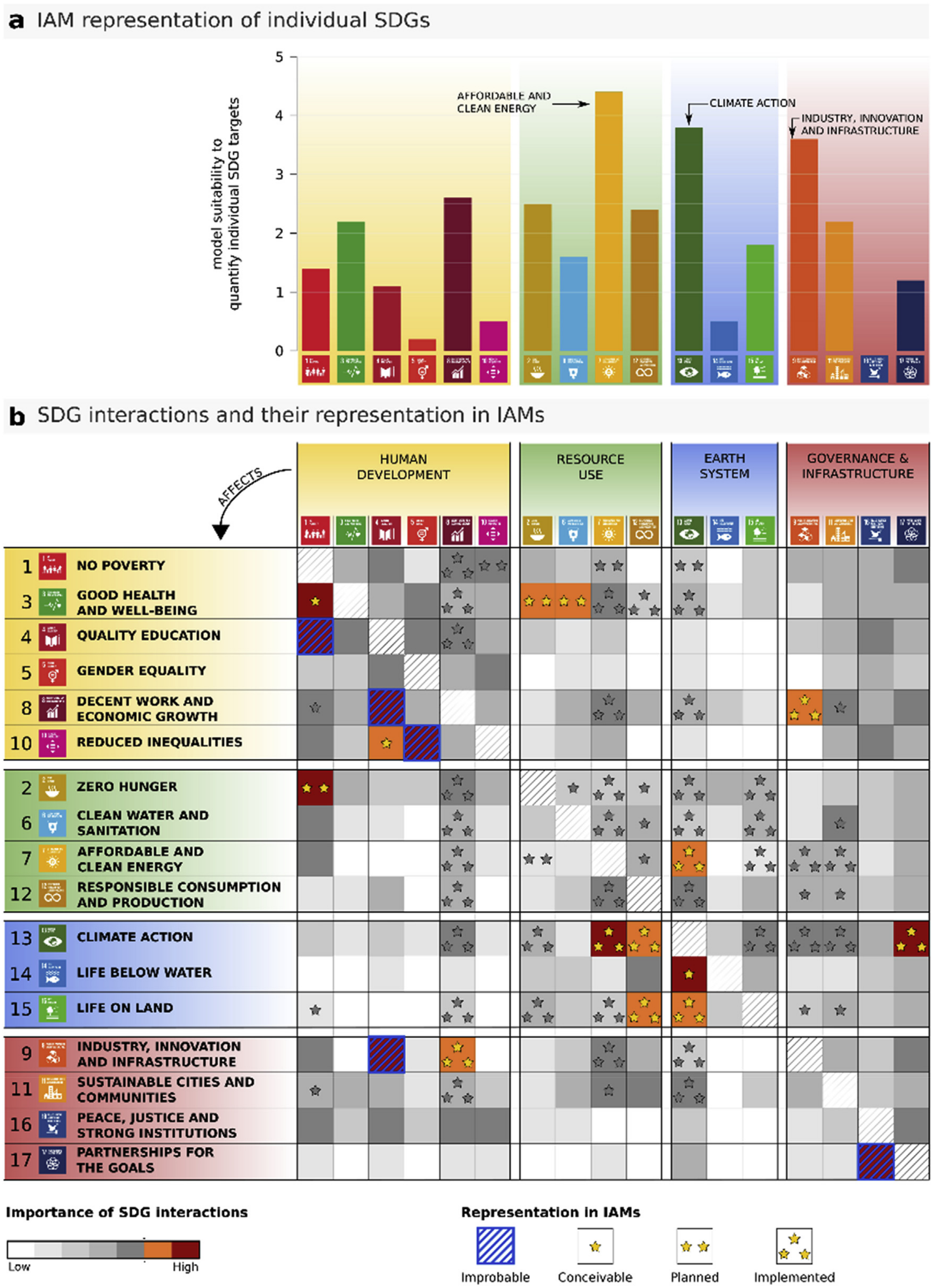


Fig. 1. The representation of SDGs by IAMs. (A): Bar height represents the average score for individual target coverage from the *model survey* (Table 1). **(B)**: SDG interactions and coverage by IAM models according to the *expert* and *model surveys* (the SDG in the column impacts the SDG in the row). The strength dimension of SDG interactions is indicated by grey shading: the darkest shade of grey represents average scores near 3 (strong interactions), while white represents no interactions. The representation of IAMs following the *model survey* is indicated by asterisks. ***: currently in IAMs, **: planned development, and * conceivable to be represented in the future. Finally, orange cells indicate the highest agreement between the importance of interactions and potential model representation, while blue coloured cells show the most notable important interactions without model representation. Interactions that are marked as currently represented are endogenous, with various levels of process detail. Future modelling of the SDG interactions that have remained unrepresented thus far can be achieved as a part of a consistent set of exogenous assumptions such as, for example, the impact of quality education on reducing poverty.

overlap in scores between the *expert* and *model surveys* (orange cells in Fig. 1), with poverty affecting hunger, hunger affecting health, and clean water affecting health being assigned the highest scores in both surveys, followed by inequalities affecting poverty, energy affecting poverty, and climate affecting poverty. This suggests that these planned model developments are supported by experts. With lighter grey in Fig. 1 (i.e. deemed less important by experts) but still representing the existing interactions, the same holds for the planned development of hunger affecting energy.

2.2.4. Potential for model development

It is perhaps more important to identify what has not been modelled rather than to identify what has. Looking at the overlap between existing interactions (grey) and interactions deemed conceivable to be modelled in the future (one star) in Fig. 1, the potential for IAMs to improve representation of important SDG interactions in the future seems to lie in the human development and resource use clusters. These are the effects of addressing poverty on health and economic growth, of (renewable) energy on cities, of education on inequalities, of climate action on oceans, and of cities on water and economic growth. Interactions that are deemed most important without current, planned, or conceivable IAM coverage (blue hatched cells in Fig. 1) mostly lie in the human development cluster, despite planned developments and potential for further improvements. These interactions include poverty affecting education, education affecting economic growth and industry, gender equality affecting inequalities, and peace affecting partnerships for the goals.

2.2.5. SDG interactions at various levels

SDG experts in the *expert survey* were asked about the scale of the problems and solutions pertaining to the SDGs (see Table S2), illustrating that SDG interactions can be both global and local. Broadly speaking, the problem dimension of most SDGs was identified as global (with exceptions, e.g. SDG 10), while the solution dimension was more often found to be local (with climate and oceans being a notable exception, being global and transboundary in nature). The ‘Means of Implementation’ targets were mostly classified as global. A few were classified as transboundary, whereas only one was classified as local (Target 7b). Most experts noted that solutions at multiple scales would be necessary for most SDGs. This may be difficult to implement in models, meaning that modellers still need to decide what solutions should be endogenously represented in the models.

2.3. Model assessment: synthesis of literature confirms model survey

We compared the results of the *model survey* with the findings drawn from a synthesis of the IAM literature. This helped identify which of the SDGs were jointly discussed in the literature. We used topic modelling [107], a machine learning method in natural language processing, to automatically identify the possible interlinkages among different SDGs across 383 papers from the available IAM literature on SDGs (see Fig. 2). In Fig. 2, topics (inner ring) were endogenously detected by our topic model. Each topic on the inner ring is related to a particular SDG in the outer ring of the graph (see Methods).[3]

The existing IAM literature focuses mostly on the interlinkages among 7 out of 17 SDGs, confirming the self-assessment of IAM modelers in the *model survey*. Almost all interlinkages involve the climate SDG (SDG 13) because climate change is a central theme of the analysed literature. In contrast, there are very few linkages among the non-climate SDGs alone. Most of these include linkages within and between the human development and resource use clusters (e.g. SDGs 7 and 8). Some interlinkages are not represented at all because they are only covered by a small number of studies and thus cannot be detected by our topic model. We believe that this is actually a feature of the analysis focusing on community practice as it only identifies interlinkages with a certain level of maturity without human bias.

As revealed by the results from the *model survey*, the most prominent interlinkages concern topics that have been of long-standing interest to the integrated assessment community, such as the link between climate stabilisation and transformations towards clean and affordable energy systems [59–63] or linkages to economic growth [64–71]. Large bodies of literature feature SDG interactions of medium importance according to experts. These discuss, for instance, the linkage between land-based mitigation options (SDG 13), in particular, bioenergy, and aspects around land competition and food security (SDG 2) [72–77], as well as water availability/security (SDG 6) [74,78–81]. Conversely, only a few studies have analysed biodiversity impacts (SDG 15) of land-based mitigation (SDG 13) [82], an interaction that has been deemed as important according to the *expert survey*. Finally, some studies have examined the air pollution implications (SDG 3) of alternate climate mitigation pathways (SDG 13) [11,83–86], even though health impacts have been studied directly only in recent times [87].

3. Conclusions and discussion

3.1. Conclusions

With the adoption of both the SDGs and the Paris Agreement, a great challenge and opportunity lies ahead for IAMs. IAMs appear capable of adapting and of including more interactions among the SDGS. The SDGs now call for further model development towards integrated sustainable development pathways (SDPs), maximising synergies and minimising trade-offs, in order to ensure policy coherence. Such SDPs should cover a more comprehensive range of SDGs and their targets and indicators, while specifically considering interactions among them (e.g. between eliminating poverty and hunger, which is an interaction that is set to be included in some of the models that participated in the *model survey*).

Forward-looking, model-based analyses of interactions are critical for informing such integrated SDPs. They supplement case studies that can only cover combinations of policies that have been implemented in the past. These pathways are important not only for assessing potential future developments and consequences but also for informing policymakers on achieving SDPs, based on a systemic understanding of human–environment interactions.

The objective of this article is to show how IAMs can contribute to the analysis of all 17 SDGs and the development of integrated policies. **We find that 3 SDGs are well-covered and 10 can at least partly be quantified by IAMs, while 4 are clearly not well covered in these models.** Areas identified for model development include oceans, consumption and production patterns, cities (in relation to public transport and buildings, including e.g. compactness/polycentrism), inequalities (especially for national models and CGEs), health (in relation to food, air pollution, climate change, and life below water and on land), poverty, and, to some extent, education (on an aggregated level, and possibly through coupling with specialised education models).

Key interactions among SDGs according to the *expert survey*

[3] See the methodology section and the SI for a complete presentation and discussion of the results, and see Fig. 3 for a comparison between results from the content analysis and from the model survey.

Table 1
Average scores (0–5) for model suitability to quantify individual SDG targets, and key indicators. Modelers were asked to assign a score between 0 and 5 to each SDG, based on the ability of their model to quantify individual targets, and provide key indicators (see also table S3). GINI: Gini coefficient representing income distribution (inequality); DALY: disability-adjusted life years; MSA: mean species abundance.

	All models	Key indicators
SDG 1	1.4	Per capita / household consumption, food/energy expenditure of households, people living below poverty line, GINI
SDG 3	2.2	Air pollution related mortality/air quality, DALY, health expenditure
SDG 4	1.1	Enrolment ratios and educational attainment, education expenditure
SDG 5	0.2	-
SDG 8	2.6	GDP(/growth), consumption, investment, economic structure, sector value added, employment, labour wages, food/water/steel/cement/energy efficiency
SDG 10	0.5	GINI, private consumption, labour share of GDP
SDG 2	2.5	Undernourishment, food availability/consumption per capita, food prices/expenditure, people at risk of hunger, agricultural productivity
SDG 6	1.6	Population with access to safe drinking water/sanitation, wastewater treatment, water stress, water used for energy, water prices, irrigation water withdrawal
SDG 7	4.4	People without access to electricity/relying on solid fuels/traditional biomass use, energy prices for consumers, share of renewable energy, energy intensity
SDG 12	2.4	Energy (renewable/fossil) resource estimates/utilization, recycling rates, labour/capital/material/energy productivities, material consumption, food waste/consumption
SDG 13	3.8	NDC and policy implementation, climate forcing indicators, adaptation costs/investments/damages, residual damage, heating/cooling demand, planting dates, and variety change
SDG 14	0.5	Ocean acidification, fertilizer use/losses, adaptation capacity of coastal areas, fisheries as % of GDP, Nitrogen cycle indicators, and MSA in aquatic ecosystems
SDG 15	1.8	Land use/cover area, forest/deforested/terrestrial ecosystems area, area under sustainable forest management, nitrogen losses agriculture, terrestrial acidification, MSA/wilderness/species richness indicators, reforestation/protection targets
SDG 9	3.6	Transport/industry energy demand, manufacturing value added/employment, CO_2 emissions per sector/per value added, travel demand
SDG 11	2.2	Travel demand/per capita, transport energy use, waste/wastewater volumes, air pollutant emissions, urbanisation rate
SDG 16	0.0	-
SDG 17	1.2	GDP per capita, economic structure, private/public consumption, investments, sector value added, exports, taxes as a % of GDP, import duties per product, share of exports of developing countries in global exports by sector, and average tariffs faced by developing countries

Table 2
Model representation of the highest-ranked currently covered interactions compared with expert-identified processes.

From SDG → to SDG	Model representation	Experts
7 → 13	Increased access to renewable energy/cleaner energy/higher energy efficiency: lower GHG emission factors and lower energy use → reduced greenhouse gas emissions (mitigation side of SDG 13)	*Access to clean cooking reduces the demand for biomass and thereby decreases related global GHG emissions (SDG 13). Improved biomass stoves reduce biofuel demand. Gaseous and liquid fuels are more efficient and therefore reduce CO_2 emissions. Electric cooking can lower emissions significantly because of the improvement in efficiency and, if generated with renewables, CO_2 neutral.*
13 → 7	Climate change mitigation policies (carbon pricing, taxes and subsidies, renewable energy targets, efficiency targets, standards, etc.) → increase in renewable energy deployment and efficiency measures. Possible negative effects of climate policy (via fuel prices) on energy access	*Climate mitigation action (SDG 13) can be used to accelerate the transition by using climate or international emissions trading to finance renewable energy development in developing countries. Technology development, for example, the global renewable energy revolution in countries like Germany and China has pushed down prices, making them more competitive with fossil fuels in generating electricity in developing countries.*
8 → 13	GDP is one of the main drivers of energy demand, resource demand, land use, and therefore GHG emissions. GDP growth increases funding capabilities to invest in climate action	
13 → 15	CO_2 concentration, temperature, and precipitation in land-use models affect vegetation growth (natural, food, and bioenergy crops). Climate change is included as a driver for the decrease in biodiversity. Bioenergy with CCS (BECCS) and afforestation/reforestation as carbon removal technologies affect land use	*The health of the planet and planetary ecosystems depend on a stable climate. Without reducing the concentrations of GHGs in the atmosphere, the systems that currently support life on earth may be jeopardized by climatic instability. Addressing this is essential for the implementation of Agenda 2030.* *Ecologically, climate change impacts marine life and terrestrial biodiversity.* *Slowing down climate change impacts will benefit natural habitats by only marginally changing their climate regimes. However, if 'renewables' from the land sector are not carefully considered in this energy transition - climate mitigation actions like BECCS can have highly negative impacts.*

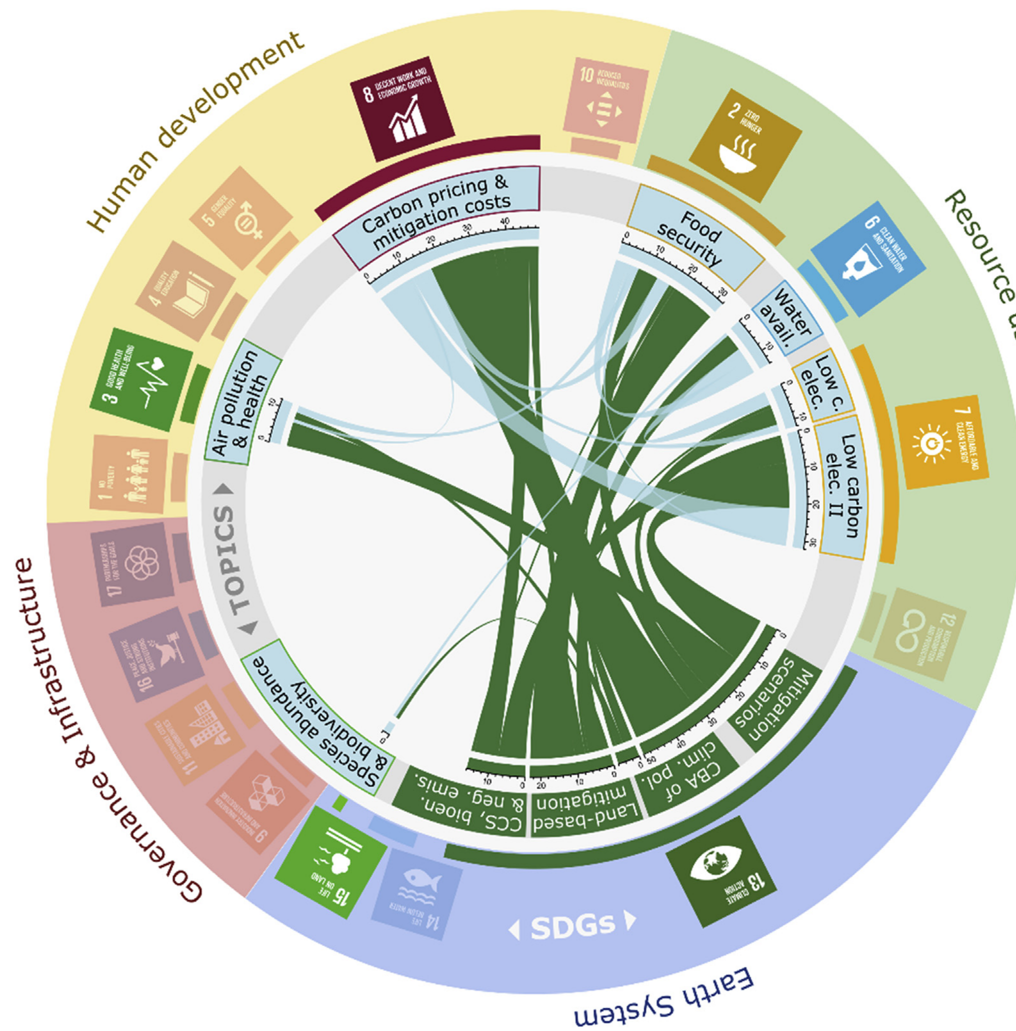
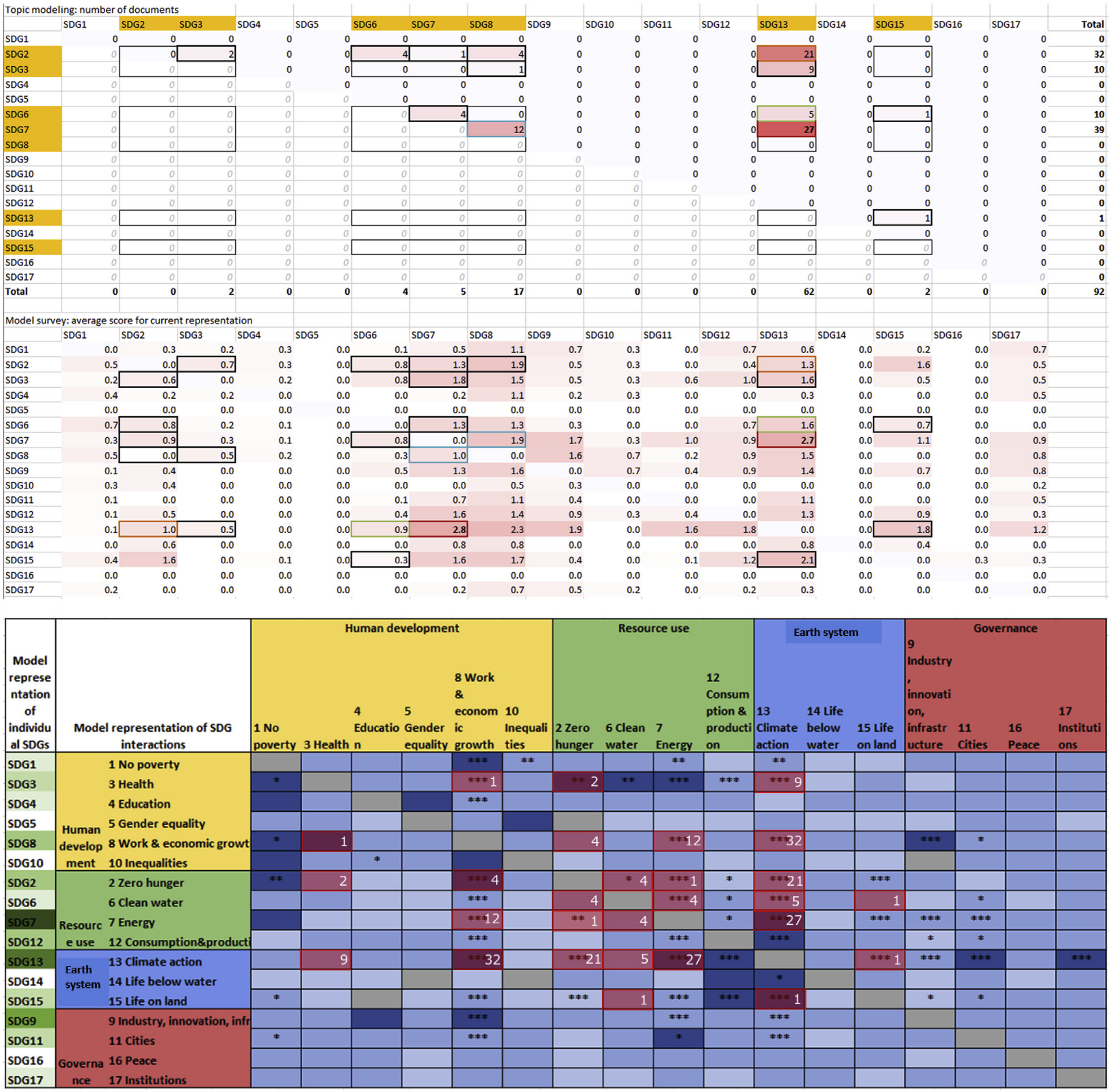


Fig. 2. SDG interactions in the IAM literature. Linkages among the topics in the literature (inner circle) have been uncovered endogenously using topic modelling. Topics are manually allocated to SDGs (outer circle). Chord width is proportional to the number of documents that simultaneously feature two topics. Climate topics are in green while non-climate ones are in light blue. Water avail.: Water availability; Low c. elec.: low-carbon electricity; CBA of clim. pol.: cost-benefit analysis of climate policy; CCS: carbon capture and storage; bioen.: bioenergy; neg. emis.: negative emissions.

were found within the human development cluster, between the human development and resource clusters, and with the Earth system cluster. Addressing many of them but with a slightly different focus because of their original design, **IAMs mainly cover interactions within and between the 'Efficient and sustainable resource use' and 'Earth system' clusters**. However, they have expanded to other fields, covering the 'Good governance and infrastructure' and 'Human development' clusters to some extent. The strength of IAMs lies in their ability to provide a global picture, highlighting the differences between regions and including displacement effects, but also between, for instance, cities and rural areas. **Planned developments include increased coverage of the human development cluster**, with interactions that have been deemed important by experts but are currently not (well) represented by the existing models. Model development is possible in some cases, but other tools may be more appropriate in other cases. Although gaps in the representation of SDG targets, indicators, processes, and interactions exist, IAMs provide a good starting point for more comprehensive SDG assessments. **IAMs have proven capable of expanding their applicability and of assessing interactions between sectors and regions** [18].

3.2. Discussion: IAM research agenda

Looking at the relevant, known, and conceivable relationships among the SDGs, we identified areas for model development while recognising that not all models need to cover all aspects and interactions. IAMs are heterogeneous. Some lend themselves better to the study of certain SDGs, whereas others are better suited for other SDGs. One limitation of the analysis is in the number of models surveyed. This limitation implies that results apply to mitigation- and process-focused IAMs, although the synthesis of the literature helped broaden the scope. As these models represent the state of the art, the findings are relevant for identifying areas for future research and for describing how current IAMs can be used in the analysis of SDGs. The resource use and human development clusters have the potential to improve the models further. This includes the effects of addressing poverty on health and economic growth (possibly through model coupling), of (renewable) energy on cities (possibly through modules or model coupling), of education on inequalities (possibly through model coupling), of climate action on oceans (possibly through model extensions), and of cities on water and economic growth (possibly through model



Topic modeling: number of documents

	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17	Total
SDG1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG2	0	0	2	0	0	4	1	4	0	0	0	0	21	0	0	0	0	32
SDG3	0	0	0	0	0	0	0	1	0	0	0	0	9	0	0	0	0	10
SDG4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG6	0	0	0	0	0	0	4	0	0	0	0	0	5	0	1	0	0	10
SDG7	0	0	0	0	0	0	0	12	0	0	0	0	27	0	0	0	0	39
SDG8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
SDG14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SDG17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	2	0	0	4	5	17	0	0	0	0	62	0	2	0	0	92

Model survey: average score for current representation

	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
SDG1	0.0	0.3	0.2	0.3	0.0	0.1	0.5	1.1	0.7	0.3	0.0	0.7	0.6	0.0	0.2	0.0	0.7
SDG2	0.5	0.0	0.7	0.3	0.0	0.8	1.3	1.9	0.5	0.3	0.0	0.4	1.3	0.0	1.6	0.0	0.5
SDG3	0.2	0.6	0.0	0.2	0.0	0.8	1.8	1.5	0.5	0.3	0.6	1.0	1.6	0.0	0.5	0.0	0.5
SDG4	0.4	0.2	0.2	0.0	0.0	0.0	0.2	1.1	0.2	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.5
SDG5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDG6	0.7	0.8	0.2	0.1	0.0	0.0	1.3	1.3	0.3	0.0	0.0	0.7	1.6	0.0	0.7	0.0	0.0
SDG7	0.3	0.9	0.3	0.1	0.0	0.8	0.0	1.9	1.7	0.3	1.0	0.9	2.7	0.0	1.1	0.0	0.9
SDG8	0.5	0.0	0.5	0.2	0.0	0.3	1.0	0.0	1.6	0.7	0.2	0.9	1.5	0.0	0.0	0.0	0.8
SDG9	0.1	0.4	0.0	0.0	0.0	0.5	1.3	1.6	0.0	0.7	0.4	0.9	1.4	0.0	0.7	0.0	0.8
SDG10	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
SDG11	0.1	0.0	0.0	0.0	0.0	0.1	0.7	1.1	0.4	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.5
SDG12	0.1	0.5	0.0	0.0	0.0	0.4	1.6	1.4	0.9	0.3	0.4	0.0	1.3	0.0	0.9	0.0	0.3
SDG13	0.1	1.0	0.5	0.0	0.0	0.9	2.8	2.3	1.9	0.0	1.6	1.8	0.0	0.0	1.8	0.0	1.2
SDG14	0.0	0.6	0.0	0.0	0.0	0.0	0.8	0.8	0.0	0.0	0.0	0.0	0.8	0.0	0.4	0.0	0.0
SDG15	0.4	1.6	0.0	0.1	0.0	0.3	1.6	1.7	0.4	0.0	0.1	1.2	2.1	0.0	0.0	0.3	0.3
SDG16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SDG17	0.2	0.0	0.0	0.0	0.0	0.0	0.2	0.7	0.5	0.2	0.0	0.2	0.3	0.0	0.0	0.0	0.0

Model representation of individual SDGs		Model representation of SDG interactions	Human development						Resource use				Earth system			Governance			
			1 No poverty	3 Health	4 Education	5 Gender equality	8 Work & economic growth	10 Inequalities	2 Zero hunger	6 Clean water	7 Energy	12 Consumption & production	13 Climate action	14 Life below water	15 Life on land	9 Industry, innovation, infrastructure	11 Cities	16 Peace	17 Institutions
SDG1	Human development	1 No poverty					***	**			**		**						
SDG3		3 Health	*				***1		** 2	**	***	***	*** 9						
SDG4		4 Education					***												
SDG5		5 Gender equality																	
SDG8		8 Work & economic growt	*	1					4		**12		**32			***	*		
SDG10		10 Inequalities			*														
SDG2	Resource use	2 Zero hunger	**	2			*** 4			* 4	***1	*	***21		***				
SDG6		6 Clean water					***		4		***4	*	*** 5		1		*		
SDG7		7 Energy					**12		** 1	4		*	** 27		***	***	***		
SDG12		12 Consumption&producti					***				***		***			*	*		
SDG13	Earth system	13 Climate action		9			** 32		***21	5	** 27	***			*** 1	***	***		***
SDG14		14 Life below water											*						
SDG15		15 Life on land	*				***		***	1	***	***	*** 1			*	*		
SDG9	Governance	9 Industry, innovation, infr					***				***		***						
SDG11		11 Cities	*				***				*		***						
SDG16		16 Peace																	
SDG17		17 Institutions																	

Fig. 3. Comparison between topic modelling results (number of papers discussing two SDGs) and *model survey* average scores for the current representation of interactions among the SDGs. Overlap can be found in all cells filled with numbers in the topic modelling overview (first matrix) corresponding to above 0 average scores in the *model survey* (second matrix). The largest number of documents corresponds to the cell with the second highest score in the *model survey* (SDG 8 – SDG 13). Interactions indicated by survey respondents not found in topic modelling relate to SDG 12 – SDG 13, SDG 2 – SDG 15, SDG 7 – SDG 15, SDG 12 – SDG 15, and with SDGs in the governance cluster. As the topics were assigned uniquely to one SDG, SDG 12 is included in the topics falling under the other SDGs, thus not showing up separately.

extensions). Model development can also include a component on improving current relationships because many IAM indicators related to SDG targets are currently based on either exogenous inputs or endogenous outputs without feedbacks ('impact indicators'), thus representing one-directional relationships. Here, a distinction can be made between 1) tracking SDG progress, for which improving the representation of SDG indicators is necessary, and 2) solutions, for which IAMs may need to improve the representation of processes relevant for the SDG indicator and the interaction dynamics. Combining models that cover a selection of these aspects can help present a broad overview. An example of this approach is the integration of life cycle assessment methods with IAMs. Doing so allows a more systematic and comprehensive analysis of the interactions between the SDGs in the resource and Earth system clusters. After the survey presented here was conducted, substantial progress was made in this area (e.g. Refs. [88,89]).

Going beyond studying how the SDGs are affected by climate policies is important. Evaluating the impact of achieving the human development goals on climate, ecosystems, and resource usage can be a good starting point.

In addition to interactions among the policy domains, interactions among different geographical scales should also be considered [90]. As Weitz et al. [2] and Moyer et al. [56] indicated, ultimately SDG targets will have to be interpreted in specific settings with appropriate formulations of the targets considering the national circumstances in question (political, economic, and social contexts). The SDG *expert survey* confirmed that SDG targets speak to multiple scales in both the problem and solution dimensions. Besides better coverage of SDG targets and their interactions, sufficient temporal and spatial resolution is necessary to assess the potential strategies for reaching the SDGs (see Table S2). Allen et al. [57] suggested that models would be most useful for the SDGs if they have a long time horizon, support analysis at the national scale (with linkages to global feedbacks), have broad sectoral coverage (supporting analysis of interlinkages across goals), and are able to simulate the transformations required for achieving the SDGs. The IAMs assessed here generally have these abilities, but the granularity is limited for several SDG-relevant aspects. The incorporation of detailed policy instruments in models is an important step in simulating the required transformations. In CD-LINKS, models have started to implement individual policy measures and targets in G20 countries in the scenarios that were developed under the project [91]. However, it is necessary to enhance model capabilities in this area. While the resolution of individual models can be increased (e.g. Refs. [92,93]), interactions among models focusing on different scales seems useful as global relationships are not necessarily the same at the local level. National and global models will need to exchange information, for example, through harmonised future storylines such as the Shared Socioeconomic Pathways (SSPs [18]) and the exchange of information on national policies and political circumstances and global boundary conditions such as carbon budgets, as was done in the COMMIT[4] and CD-LINKS[5] projects, for instance. Global models will be necessary to fully capture global SDG processes, while national IAMs and other tools and models are necessary for higher spatial and temporal resolution, for example, for assessing energy access targets [57]. It is necessary to go beyond scale and move away from averages towards explicit modelling of heterogeneity as many SDGs are distributional issues, especially human development goals (see e.g. Ref. [94]). This could be done endogenously, or by building more detailed modules and linking them to the integrated assessment framework.

3.3. Discussion: cooperation and interdisciplinarity

Although many gaps can be closed by integrating more SDG dimensions in IAMs, full endogenisation of all interactions is not possible (e.g. because of numerical limitations or lack of clear-cut dynamics) and is probably not desired in some cases. In such cases, linking different disciplines through exogenous assumptions and a common narrative is an alternative option. This approach was formalised and put into operation as part of the SSPs [18,95]. This holds true especially for targets related to the institutional and social dimensions of the SDGs that are often crucial for enabling other SDGs. IAMs will need to cooperate more closely with social sciences, as understanding biophysical processes is no longer sufficient while studying SDGs (e.g. demography, governance, and poverty research). This could, however, increase intrinsic uncertainty in projections, thus necessitating the careful communication of results. Whereas using a consistent set of exogenous assumptions rather than endogenisation cannot fully capture feedbacks, it can be a good starting point. Closer cooperation within the IAM community can contribute to closing gaps, for example, by applying different IAMs, each according to their strengths, in one framework (as, for example, already done in the development of the SSPs, with each model detailing one storyline such as the one for SSP1). Future research can examine the overview of how interactions are modelled with experts on associated SDGs (such as those in the *expert survey*), given the importance of uncovering the mechanisms underlying the interactions identified.

As Fig. 1 (blue hatched cells) showed, many interactions that were deemed important are neither covered by IAMs nor conceivable to be represented in the future. These include the effects of, for example, SDGs related to human development and governance and infrastructure on many other SDGs. However, these interactions can still be covered to some extent, for example, in more abstract ways or, most importantly, by linking with other tools and communities. Such an approach relates to the modular operation of IAMs. Looking at the effect of other SDGs on each cluster highlights the potential for studying how human development goals affect each other, as well as resource use and Earth system SDGs. Future research can focus on these interactions and expand the analysis by explicitly identifying and empirically testing the causal links underpinning the interactions classified in the *expert survey*.

Multi-model frameworks can help fill some of the gaps related to both scale and topic. Soft-linking to other more qualified models can also be a good starting point, possibly even moving to integrated assessment frameworks that include these different models. Such multi-model frameworks can help capture multi-sectoral dynamics that are not endogenous to the models themselves. As decision-support tools, these frameworks can provide information at finer spatial and temporal resolutions while maintaining consistency with global boundary conditions (e.g. Refs. [91,96–98]). Beyond modelling, however, IAMs will need to be combined with empirical research to bring in the local context and experience pertaining to strategies that work in different settings, as IAMs cannot and probably should not even try to represent everything. Although empirical research on interactions has been going on, for example, in climate impact studies, a major shift is necessary to help translate IAM results into concrete policy recommendations.

3.4. Policy implications

IAMs have already informed global and national policy on climate change mitigation, both through IPCC assessments and, for example, with individual model applications such as the International Futures [30] and iSDG [29] models and several national energy system models [99]. These tools can promote policy coherence for the SDGs, by structuring complexity, exploring uncertainties pertaining to the impact of policies with scenarios, and reconciling contested views through common narratives, including by bringing different ministries together. They can help track dynamics, including trickle-down effects of various policy targets and instruments, and second-order interactions, to help policymakers identify and minimise trade-offs while maximising synergies.

4. Methods

4.1. SDG expert survey

Expert consultation is useful in investigating interactions among the SDGs, because experts can appraise causality, that is, the processes underlying the observed and identified synergies and trade-offs, which correlation analyses would not be able to provide. It is also complementary to the literature review, indicating the

[4] https://themasites.pbl.nl/commit/
[5] https://www.cd-links.org/

relevant relations that are not covered in the literature. The SDG experts were identified and selected through the following process:

1) Subject experts involved in the Elsevier study on sustainability science [100] were chosen first.

Gaps in the coverage of SDGs were filled with the following sources:

2) Experts who drafted the UN Global Sustainable Development Report (2019);
3) All those who were invited to attend the meetings of the 'The World in 2050' project regardless of whether they attended the meetings;
4) Authors of the ICSU/ISSC review of the SDG targets [101];
5) Members of the professional IISD SDG mailing list (listserv).

The survey was piloted with a small subset of the target group to ensure that the questions were clear. After this, each expert in groups 1 to 4 was contacted individually via email. The aim of the survey was explained. They were invited to provide suggestions for additional experts that we could contact (snowball sampling technique). A total of 20 experts participated in the survey (19% of the 105 contacted, see Supplementary Material for an overview of the number of experts per SDG), conducted from 2 November 2017 to 14 March 2018. For group 5, the same email was sent to the mailing list, but with a different hyperlink to a copy of the survey (conducted between 27 November 2017 and 14 March 2018), so responses could be tracked separately. For this group, additional questions pertaining to the respondents' backgrounds and areas of expertise were added (see Supplementary Material) in order to filter responses of this self-selected group (given that they were invited through an anonymous email list rather than approached individually). To be included in the matrix, experts had to have a self-assigned score of above 6 for level of knowledge on the topic (i.e. 7–10), resulting in 30 useful responses from group 5, additional to the 20 responses from groups 1 through 4, that is, 50 in all. Except for SDG 5, all SDGs were covered at least once, but the distribution was skewed towards SDGs 7, 11, 15, and 17.

Two types of biases can be distinguished in expert elicitations: motivational (related to personal interests and circumstances) and cognitive (related to heuristics, and originating from the incorrect processing of information) biases [102]. The former can be limited by framing questions appropriately and asking for an honest response. The latter are more difficult to control but were considered as playing a minor role in this survey. For example, the *availability, anchoring, and adjustment* and *representativeness* heuristics were expected not to play a role, as the probability of events did not have to be assessed. Asking the experts to use a given framework to score the interactions ensured standardised responses (the seven-point typology by Nilsson et al. [5], which does not measure the strength of interactions but only classifies them as follows: -3 for cancelling, -2 for counteracting, -1 for constraining, 0 for consistent, +1 for enabling, +2 for reinforcing, and +3 for indivisible [12]). *Overconfidence* is more likely to affect the results, although the framework for scoring interactions consisted of qualitative descriptions of each score, which enabled the mapping of each interaction to the most appropriate description rather than merely assigning numbers. Structured protocols for expert elicitation can also help reduce biases further. However, they are generally aimed at addressing questions with probabilistic or quantitative responses and in-person meetings, such as the IDEA protocol as described by Hemming et al. [103], which do not apply to this study.

The survey was administered online for geographical flexibility and cost-effectiveness, and to provide respondents with the option to take the survey anytime (including pausing and continuing later). It consisted of four question groups that were aimed at eliciting standardised results and included 'no answer' options to avoid forced choices. Future research can consider applying the Delphi method [104], in which experts can react to information from and explanations offered by other experts in a number of iterations. This would refine and enable the analysis of uncertainty in expert judgement.

Experts were asked to fill in only information that pertained to the areas of their expertise and at the level of the SDGs. Some respondents raised concerns saying that the scores at the SDG level were meaningless because the interactions among targets vary and result in the co-existence of synergies and trade-offs at the SDG level. Therefore, the sign (positive or negative) was not used. Wherever possible, respondents were asked to specify target-level interactions.

4.1.1. Survey questions

1) Which SDG best covers your field of expertise? (Broader interpretation of SDG than the strict formulation of goal and targets allowed, and please specify interpretation of SDG13).
2) How would you like to answer the next question? 1) Fill in one matrix at once, both for how your SDG affects other SDGs and how it is affected by others or 2) In two separate questions, one for how your SDG affects other SGs, one for how your SDG is affected by others
   a. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Please do so in the following way: - Use the column to indicate how your SDG affects other SDGs, i.e. the effect of your SDG in the column on the SDGs in the rows - Use the row to indicate how your SDG is affected by other SDGs, i.e. the influence of SDGs in the columns on your SDG in the row. As such, you will only fill one row and one column of the matrix. In filling in the matrix, please score the interactions, using the ICSU framework see picture below; [12]. I.e. 3 indivisible, 2 reinforcing, 1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and unclear if there is an interaction, but the direction is not clear. As this question only allows numerical input, both N/A and unclear are separate columns/rows. Source: ICSU (click picture to enlarge). If you can, please specify target-level interactions in the next question.
      i. Optional comments
   b. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Could you please score the interactions, using the ICSU framework (see picture below)? I.e. +3 indivisible, +2 reinforcing, +1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and unclear if there is an interaction, but the direction is not clear. Source: ICSU (click picture to enlarge). In this part, please assign scores only for how your SDG is affected by other SDGs (i.e. the influence of SDGs mentioned in the columns on your SDG). If you can, please specify which targets are affected in the next question.
      i. Optional comments
   c. Could you please indicate how the SDG that covers your field of expertise interacts with other SDGs? Could you please score the interactions, using the ICSU framework (see picture below)? I.e. +3 indivisible, +2 reinforcing, +1 enabling, 0 consistent, -1 constraining, -2 counteracting, -3 cancelling. Please use N/A for no interaction between the two SDGs, and

unclear if there is an interaction, but the direction is not clear. Source: ICSU (click picture to enlarge). In this part, please assign scores only for how your SDG affects other SDGs (i.e. the influence of your SDG on the SDGs mentioned in the rows). If you can, please specify which targets are affected in the next question.

i. Optional comments

3) Looking at the individual SDG for your field of expertise, would you describe it as a local, transboundary or global issue?
   a. Problem
   b. Solution
4) Further comments; please leave your e-mail address if you are interested in the outcomes.

4.1.2. Processing of results

Fig. S4 colour codes the interactions based only on the *expert survey* in which combined scores of 0 are grey and scores between 1 and 3 move from lighter to darker blue, while the scores between -1 and -3 move from lighter to darker red. Multiple responses in one cell of the interaction matrix were combined with the mode wherever possible (i.e. most occurring score, being -3, -2, -1, 0, 1, 2, or 3), and maximum wherever it was not possible. For Fig. 1, individual responses from the SDG *expert survey*, after removing the sign (i.e. -2 was recorded as 2) were combined with individual responses from the *model survey* question on the 'importance' of interactions, by averaging them with equal weighting of all individual responses. This score aggregation was necessary for the integration of all the experts' responses into the same question in two different surveys.

4.2. Model survey on representation of SDGs and interactions among SDGs

The survey was conducted among modellers who participated in the CD-LINKS project. The CD-LINKS project analyses the interplay between climate action and development to inform the design of complementary climate–development policies. It is, thus, well suited for the objective of this study.

The interpretation of SDG targets and indicators deserves attention while studying the representation of SDGs in IAMs. We have adhered to the SDG indicators that were formulated by the inter-agency expert group on SDG indicators (IAEG-SDG) [105] as far as possible, but also included other IAM indicators that were thought of as representing the SDG targets well. This is especially true for SDG 13 (climate action), which focuses on resilience, climate strategies, and education, and refers to the UNFCCC. The IAEG-SDG indicators for this goal (mostly 'number of countries that have/adopt… policies') can generally not be modelled by IAMs per se, but IAMs do report many other highly relevant climate-related indicators. A broader interpretation of SDG targets and indicators is necessary to reflect the physical linkages included in IAMs, beyond the 'political' linkages among the SDGs (see also [106]). Indirect or second-order interactions were not considered. Internal links (e.g. from SDG 2.4 to SDG 2.1) were excluded from the analysis in order to focus on interactions among the SDG areas. The same holds true for targets that are in some way a sub-target or element of another (umbrella) target (e.g. 6.2, access to sanitation, and 7.1, access to energy, can be considered elements of 1.4, access to basic services): these 'links' were excluded from the analysis, but they represent policy coherence thinking within the SDGs. The so-called 'Means of implementation' (a, b, c sub-targets) were also excluded from the analysis. SDG 17 was included, but it can be considered a 'means of implementation' and is difficult to measure. SDG 17 is, however, part of the rationale for this study, highlighting the importance of policy coherence for sustainable development. China TIMES and IPAC were only included in the assessment of the representation of individual SDG targets and not in the assessment of interactions, as that part of the survey was not filled in completely.

4.2.1. Survey questions

1) *Model representation of individual SDGs (now):* Please indicate the suitability of your model to represent a certain SDG by a score of 0 (not suitable) to 5 (very suitable). Also indicate maximum 5 key indicators that your model could provide for that particular SDG.
2) *Model representation of individual SDGs (planned):* Same as previous sheet but include planned model development.
3) *Important interactions:* We would like you to assess the importance of the interactions between different SDGs. Clearly, these interactions can go in different directions. Therefore, please assume that the rows indicate the target SDGs and the interaction thus indicates how important the other SDGs are for achieving the row. We would like you to assess the importance of the interactions between different SDGs. Clearly, these interactions can go in different directions. Therefore, in answering, do not restrict yourself to only those interactions that can be modelled: the idea is to score all possible, important, interactions. We would like you to score the linkages on a scale of 0 (no or very little impact) until 3 (strong impact). Not necessary to fill in the 0 values (no number is assumed to be zero).
4) Modelled *interactions (now):* Please fill in the interactions between the different SDGs as represented by your model. Indicate each link by scores 0 (not represented) to 3 (plays a key role in the model). If possible, please specify the modelled interactions at the target-target level (e.g. SDG 7.2–6.3).
5) *Modelled interactions (planned):* Same as previous sheet but include planned model development.
6) *Modelled interactions (conceivable)*: Please fill in the interactions between SDGs that are conceivable to be modelled by IAMs, i.e. score the interactions identified in step 1 for representation in IAMs in general.

4.2.2. Processing of results

Scores were averaged across all the models for each question. As personality or cultural biases may have entered while assigning levels to represent the SDGs adequately in the models, teams were asked to map their 0–5 scores onto a scale with descriptions for normalisation (see SI), although all model teams used the full 0–5 range. Based on the mapping, original scores for two models were revised before averaging (see SI). Three stars were assigned to Fig. 1 when the average score in question 4 was at least 1, two were assigned when the average score in question 5 was at least 1, and one was assigned when the average score in question 6 was at least 1. For the colours in Fig. 1, individual scores of question 3 were combined with individual scores from the SDG *expert survey* (see above). The SI also shows a table with colours assigned based only on the *model survey*, where average scores below 1 were left blank and average scores between 1 and 3 were colour coded from lighter to darker orange.

4.3. Synthesis of literature: topic modelling

We applied topic modelling to identify well-established interlinkages among different SDGs in the available IAM literature. Topic modelling refers to a suite of algorithms that aim to unravel the latent thematic structure of a large and unstructured collection of documents [107]. The idea here is to discover this thematic structure, link the identified themes or topics to SDGs where appropriate, and analyse the co-occurrence of SDG-related topics in documents. By doing so, we can obtain a bird's eye view of the interlinkages that have been substantively discussed in the literature so far. Our methodology proceeded in three steps:

- Identifying the literature base;
- Discovering the latent thematic structure of the identified literature; and
- Linking topics/themes to SDGs.

These steps will be discussed below.

4.3.1. STEP 1: identifying the relevant literature

To generate meaningful results, it is crucial for our literature base to be broadly representative of the studies on integrated assessment modelling. For this study, integrated assessment modelling has been defined as any model describing key processes in the interactions between human development and the natural environment. Different types of models were developed with varying levels of detail and focus areas. These models are all included here.

We developed a dedicated literature identification strategy with two major components. The first component relied on expert surveys. Within the CD-LINKS project consortium, we asked all 17 modelling teams to provide comprehensive reference lists attesting to their past activities related to SDG themes. Of the 17 teams, 12 responded. We also asked all members of the Integrated Assessment Modelling Consortium (IAMC)—the major community organising initiative within integrated assessment—to provide lists of publications for their respective models as well, and 9 teams responded. The second component involved adding the remaining publications from major model inter-comparison exercises, namely EMF-27 [51], PATHWAYS, CD-LINKS, and LIMITS.

We collected 429 documents in all. Of these, we were able to obtain the full text versions of 402 documents. We discarded model documentations [15] and protected pdf files [4] from the sample, because our text extraction tool could not read them. We ended up with 383 documents for our analysis: 299 peer-reviewed articles and 84 working papers, reports, book chapters, and theses. Our sample does not cover the entire integrated assessment literature because of 1) the differences in responses across teams, and 2) better coverage of more recent publications. To the best of our knowledge, this is the most comprehensive review of the IAM literature related to SDGs to date.

The sample is broadly representative of the literature because of the comprehensive involvement of the integrated assessment community. For the sake of validation, we compared the results from topic modelling with the independent model expert evaluation of the existing modelling capabilities for SDG interlinkages. Within the limits of topic modelling (interlinkages of individual pioneering studies cannot be identified, see below), this comparison confirms the results from our topic model and provides a two-way validation of our results.

4.3.2. STEP 2: topic modelling

Several additional preliminary steps are necessary before applying topic modelling. First, we extracted the entire text from the 383 documents that served as our text corpus for the analysis that followed. We filtered out sections containing irrelevant information for our assessment, such as references and appendices. We processed our literature corpus by stemming and removing punctuations, numbers, and stop words. The result was used to generate a document-term matrix that comprised the term frequencies in the documents. We used the popular Term Frequency-Inverse Document Frequency (TF-IDF) term-weighting scheme to ensure that common words were filtered out of the corpus. This statistic combines the measures of term-frequency with inverse-document-frequency to give more weight to terms occurring frequently over a small number of documents and less weight to terms occurring in several or all documents or to terms that occur fewer times in a document. This procedure can also be seen as a means to remove noise.

Next, we applied topic modelling to uncover the latent thematic structure of our text corpus. Topic modelling proceeds on the assumption that words systematically co-occur within certain documents, and that repeated co-occurrence indicates a shared semantic structure across the corpus [107]. We used Non-negative Matrix Factorisation (NMF), which is an unsupervised machine learning algorithm [108,109] that has been used in a number of previous scientific studies to identify topics in corpora [110–113]. NMF factors the document-term matrix into a document-topic matrix and a topic-term matrix. The document-topic matrix provides a measure of topic prominence in documents whereas the topic-term matrix provides a description of topics by ranking the terms associated with them. As the number of topics needs to be specified exogenously, we ran NMF with different numbers of topics (i.e. 10, 12, 14, 16, 18, 20, 25, 35, 40, 50, and 60). The resulting allocations of documents and terms to topics were then manually and independently analysed by multiple people. We found that 14 topics provided a meaningful synthesis and classification of the literature and covered a broad spectrum of themes while minimising the number of topics with little additional information (i.e. overfitting).

4.3.3. STEP 3: linking topics/themes to SDGs

We characterised each topic based on the key features revealed through a study of high-scoring documents and their most prominent keywords. The results are presented in Table 3. Topics at the top of the table have a higher marginal distribution and are more frequent in the integrated assessment literature. A more comprehensive discussion of results can be found in the SI. Next, we manually matched the topics to the SDGs. Matches can occur more generally at a goal-level or more specifically at a target-level. We reviewed documents that scored highly on a particular topic and compared them with the relevant SDGs and targets. For example, the topic on mitigation scenarios [1] deals with mitigation strategies and emissions reduction. It contains many documents that deal with climate change mitigation in line with the international climate goals. However, it does not relate to any of the more specific targets. We therefore matched it at the goal level. The topic on food security [4], on the other hand, directly relates to different targets under SDG 2, and to related indicators such as the ones on agricultural productivity (2.3) or sustainable food production (2.4). Of the 14 topics, 3 did not relate to any SDG [3,11,12].

Finally, we identified documents that substantially deal with SDG interlinkages. We assumed that such a substantial interlinkage occurs if a paper deals with two topics that relate to two different SDGs and the related topic scores pass a certain global threshold. To do so, we asked multiple team members to assess the topic quality in papers at different thresholds. We identified this threshold at a topic score of 0.1. We then removed the interlinkages between topics within the same SDG.

We do not claim that our topics cover the SDGs comprehensively. The coverage differs considerably in terms of the number of relevant topics for a particular SDG (see Fig. 2), but equally in terms of the relevance of an individual topic for a particular SDG. Through the text, we interpret our results very carefully. Any link identified is seen as evidence for research that is relevant to some aspect of

Table 3
14 topics synthesising the content of the available IAM literature. For each topic, the manually allocated SDG and the top 5 stemmed keywords are provided. The marginal topic distribution is a measure of the importance of a topic across the literature.

ID	Topic name	Stemmed keywords	Marginal topic distribution	SDG
1	Mitigation scenarios	emiss, reduct, scenario, mitig, cost	17.46	13 – target*
2	Carbon pricing and mitigation costs	price, carbon, scenario, sector, product	16.51	13 – target
3	Sustainable transitions and governance	transit, govern, actor, social, sustain	14.25	None
4	Food security	food, crop, scenario, product, yield	12.27	2 – target**
5	CCS, bioenergy, and negative emissions	CCS, scenario, fulltech, technolog, bioenergi	11.01	13 – goal
6	Land-based mitigation	land, bioenergy, crop, forest, product	10.11	13 – goal
7	Low-carbon electricity	plant, power, brazilian, brazil, csp	10.09	7 – target
8	Air pollution and health	pollut, air, emiss, aerosol, forc	9.34	3 – target
9	Water availability and consumption	water, irrig, withdraw, cool, river	9.22	6 – target
10	Low-carbon electricity II	nuclear, technolog, electr, power, wind	9.12	7 – target
11	Energy security	secur, oil, scenario, indic, divers	7.65	None
12	SSP scenario framework	ssps, scenario, rcp, narrat, socioecono	7.34	None
13	CBA of climate policies	Damage, cost, adapt, mitig, dice	7.00	13 – goal
14	Species abundance and biodiversity	speci, dispers, biodiverse, msa, migrat	4.04	15 – target

the respective interlinkages. We leave it to the other components of this paper to qualify them in very concrete terms. We also acknowledge that we only find interlinkages in fields in which the literature has already begun to mature. Pioneering studies that deal with new interlinkages will not be identified by this procedure. Yet, we see this as a feature of our analysis here as it shows the areas of substantive research alone.

Based on the stemmed keywords belonging to each topic (ordered by importance) and a thorough look at the documents pertaining to the topics, the topics were manually associated with the SDGs and targets (see Table 3). Of the 14 topics, only 11 were associated with an SDG target or goal.

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Author contributions

HvS designed, distributed, and analysed both surveys, collected inputs for the literature review, and designed the paper. DvV contributed to paper design and analysis of survey results. MH contributed to the *model survey*. VK contributed to the design of the SDG *expert survey*. KR contributed to paper design and *expert survey* distribution. JM contributed to the literature review. JH performed the literature review and formatted the figures in the main text. AP and GL contributed to the *model survey*. All authors participated in writing the paper.

Data and materials availability

The datasets generated and analysed in this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

There are no competing interests to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.glt.2019.10.004.

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